Long-Baseline Neutrino Program in the U.S.

Gina Rameika

Fermi National Accelerator Laboratory

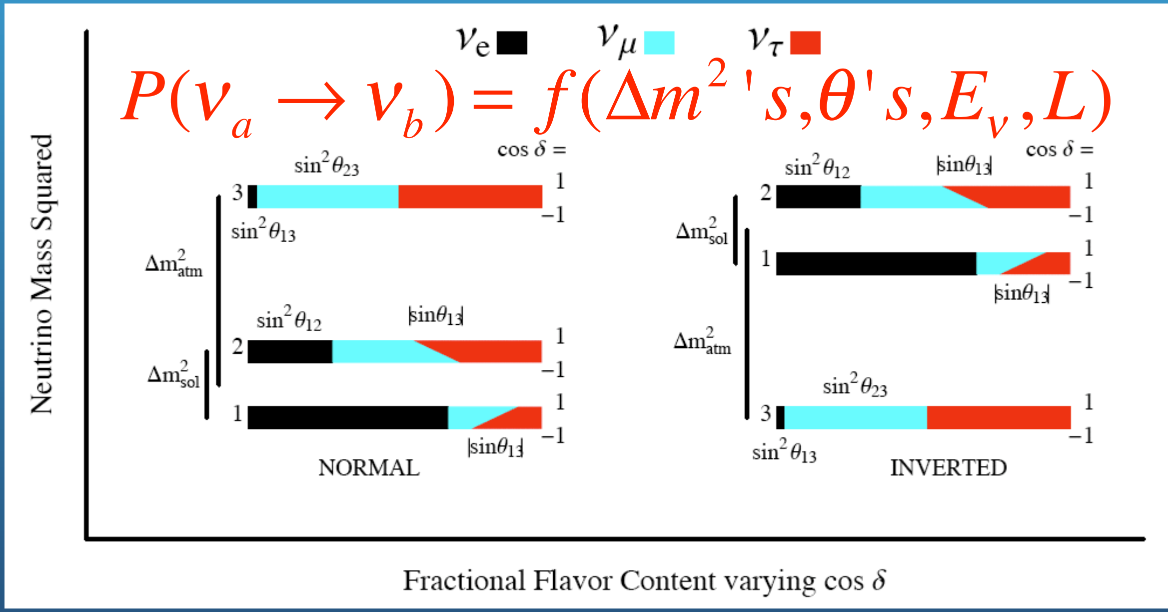
Intensity Frontier Workshop
November 30 – December 2, 2011

Outline

- Long-baseline Strategies
- Optimizing the experiment configuration
- Where we have ended up
- Summary and Conclusions

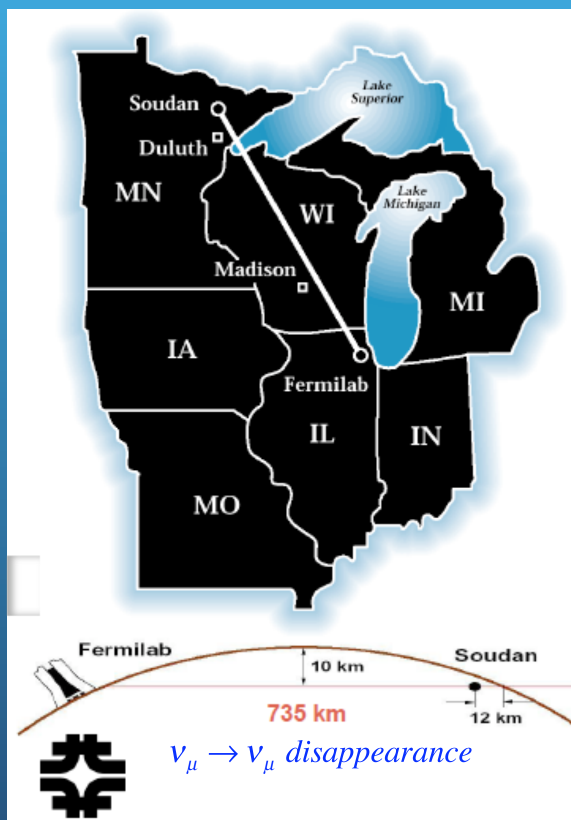
Ingredients in a long-baseline neutrino experiment

- Proton source
- Neutrino beam, E(nergy) matched to L(ength)
- Near detector (good idea)
- Far detector of mass M, a distance L from the neutrino source

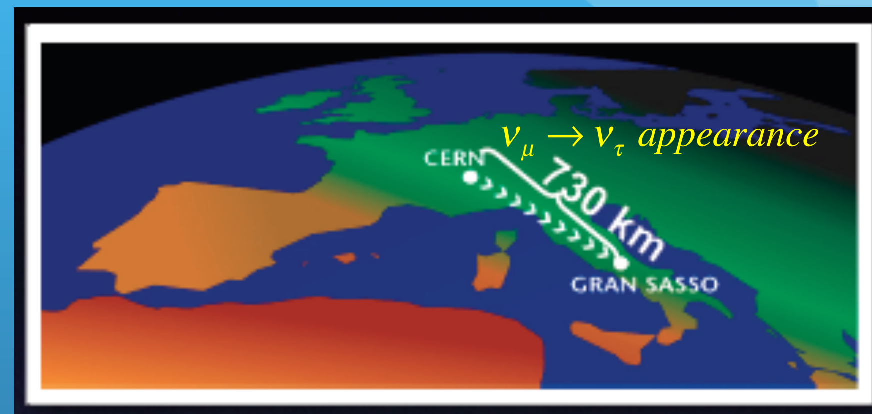


Three Beams in Operation – each focused on different oscillation channels

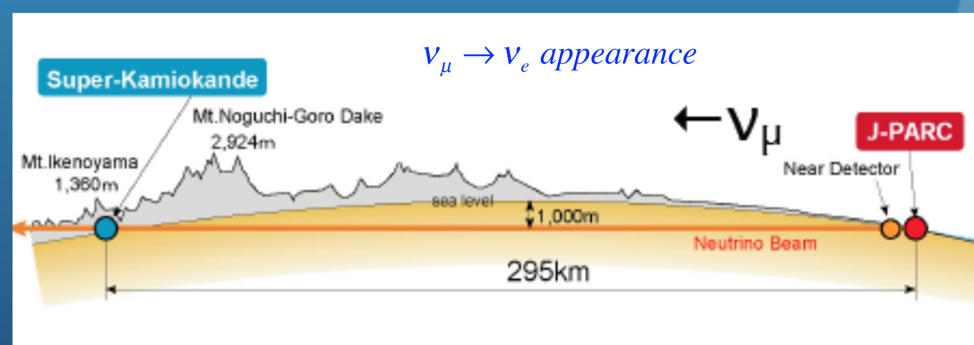
- NuMI (FNAL to Soudan)



- CNGS (CERN to Gran Sasso)



- T2K (JPARC to Super-K)

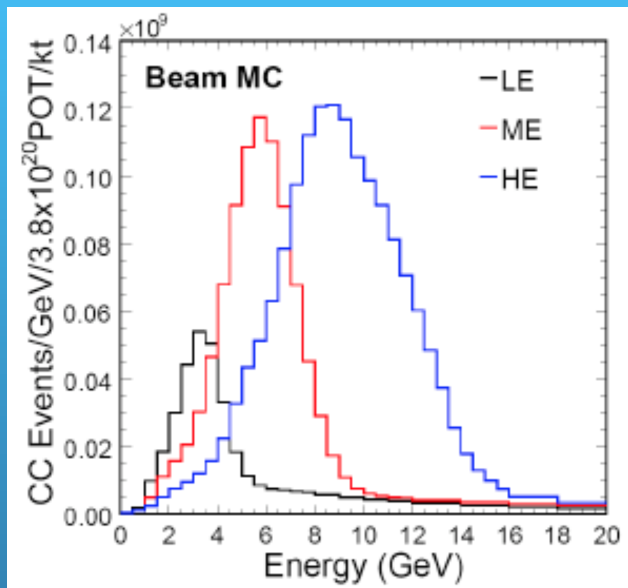


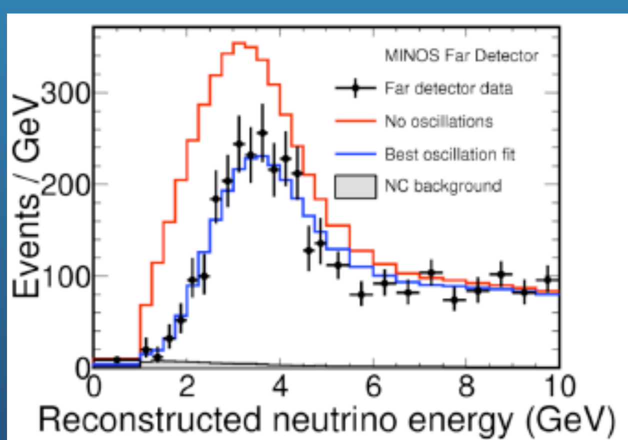
Ask the question – What has driven the choice of these configurations?

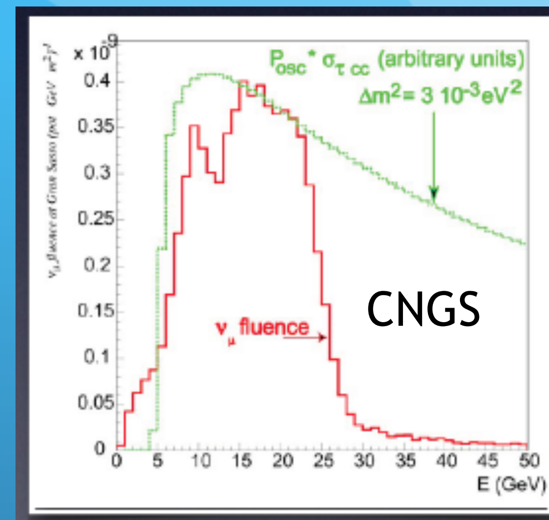
- Baseline, *L*, has been driven by the existence of facilities : Laboratories and/or detectors
  - Fermilab and Soudan Underground Laboratory -> MINOS
    - (FNAL to IMB had also been an option in the mid-90's)
  - CERN and Gran Sasso Laboratory -> OPERA, ICARUS
  - KEK (later JPARC) and Super-K -> K2K, T2K
- Energy, *E*, has been tuned by using the proton energy, neutrino beam configuration (target, horns and decay) and the angle between the beam axis and the detector to match the baseline and physics requirements

Configurations get optimized for the physics

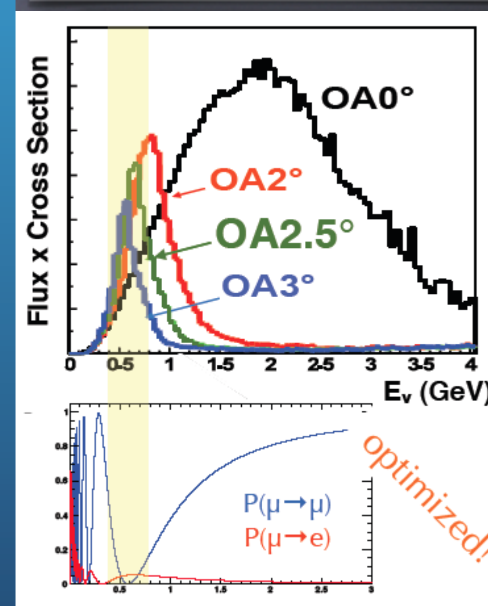
NuMI to MINOS





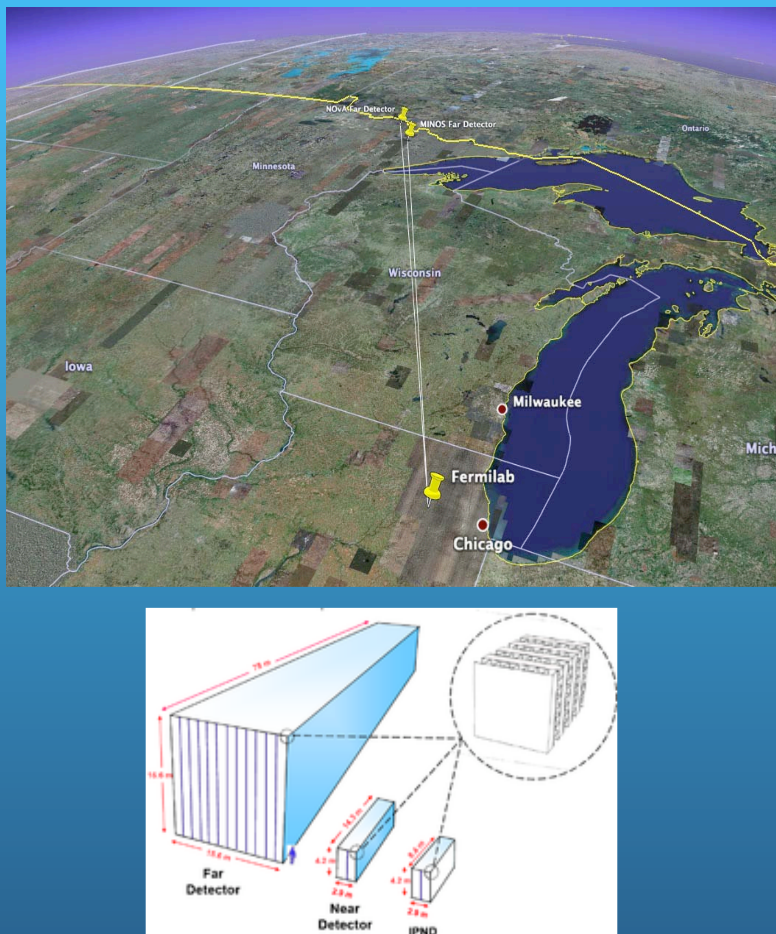


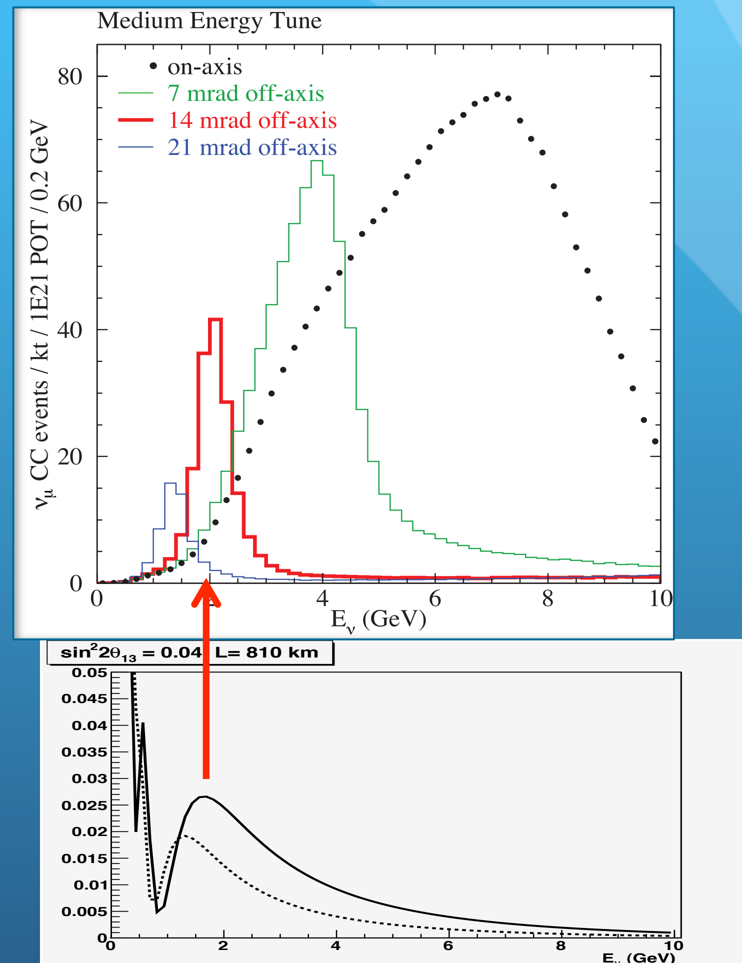
T2K



- For these 1st and 2nd generation experiments we have been able to exploit existing facilities with relatively modest construction projects and reasonable timescales
- We now need to ask, what configurations are needed to go to the next level of measurements of neutrino parameters, namely mass hierarchy and $CPV(\delta_{CP})$
- What do we need for L and E ? What do we need for detector mass, M?

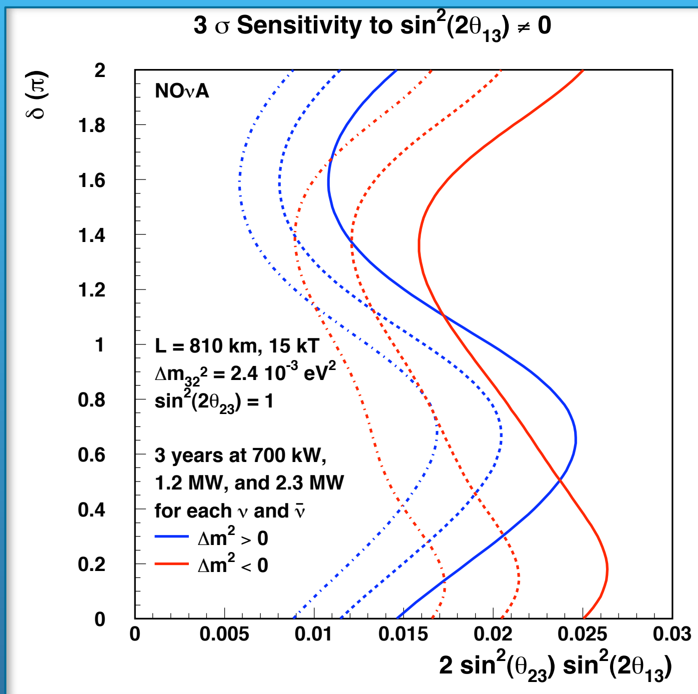
NuMI to NOvA : exploiting our investment

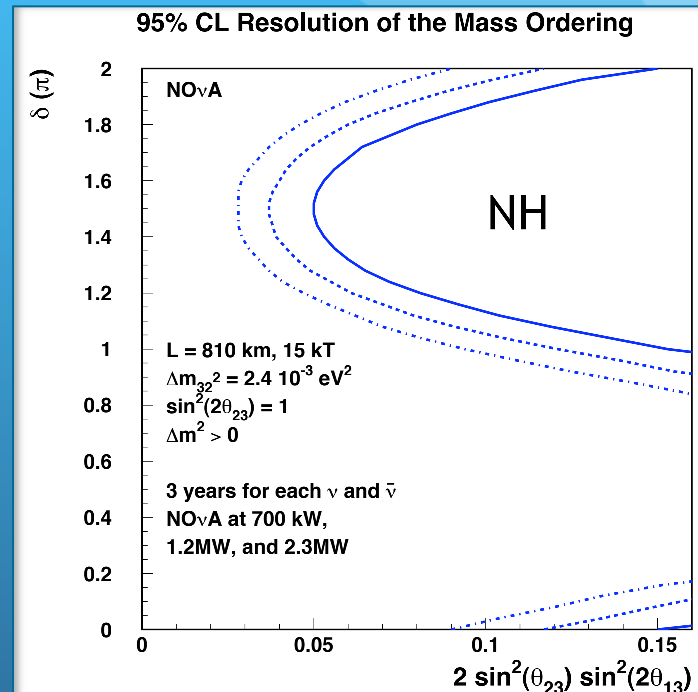




$\nu_\mu \to \nu_e$ appearance with sensitivity to the mass hierarchy from the matter effect

NOvA reach in θ_{13} and Mass Hierarchy



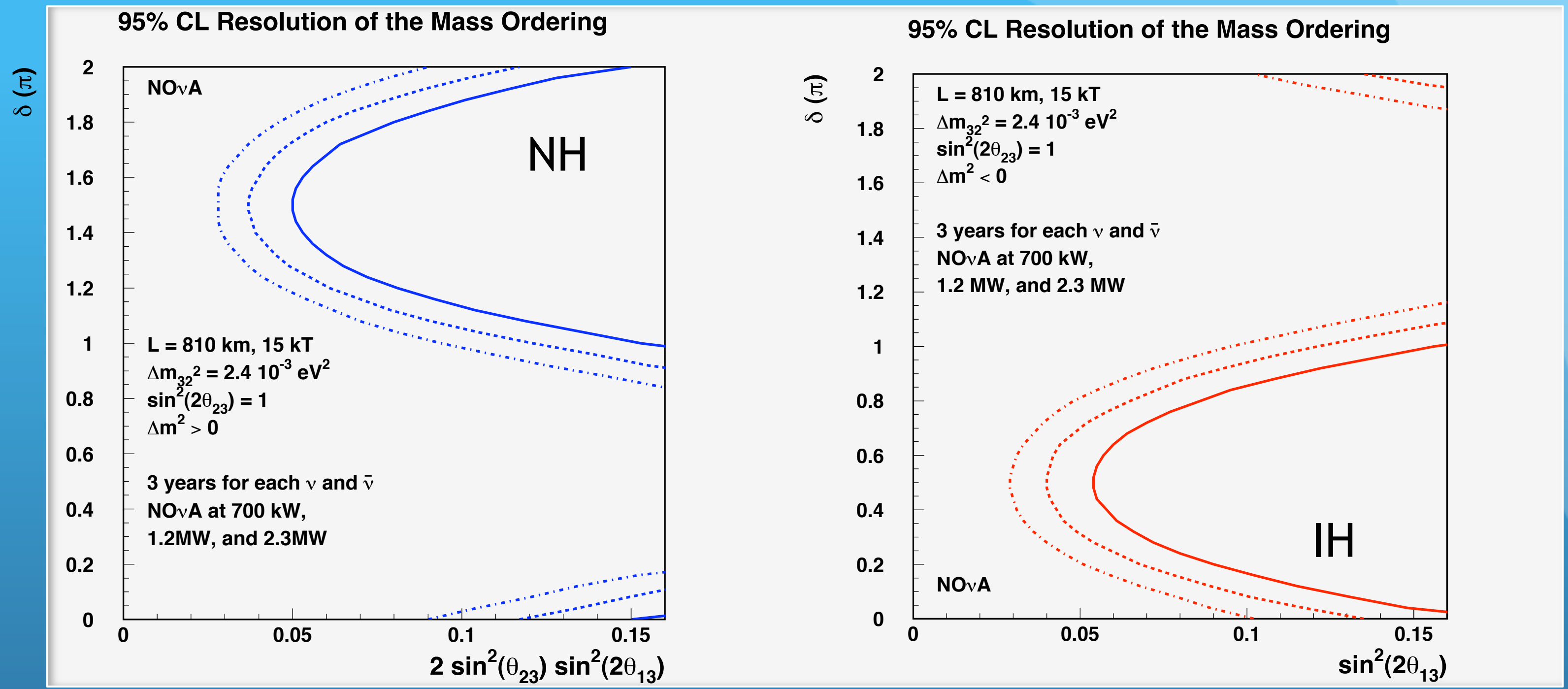


3 sigma for all values of δ
$\sin^2 2\theta_{13} \gtrsim 0.025$

1st measurement of ν_e appearance with ν and $\bar{\nu}$

For $\sin^2 2\theta_{13} \gtrsim 0.05$ there are values of δ for which the MH should be resolvable

NOvA and Mass Hierarchy



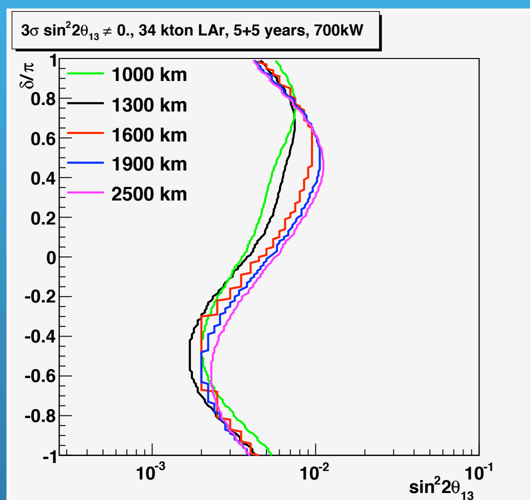
NOvA's limitation in determining the Mass Hierarchy comes from the arrangement of the matter-cp effects which depend on the length of the baseline; it's long, but just not long enough to ensure discovery ; in fact we need to get lucky; we may learn something interesting ;

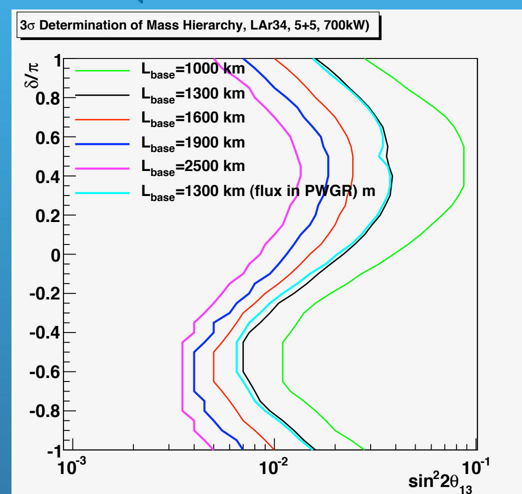
The U.S. has a lot of land → potential for *long*-baseline to increase the matter effect

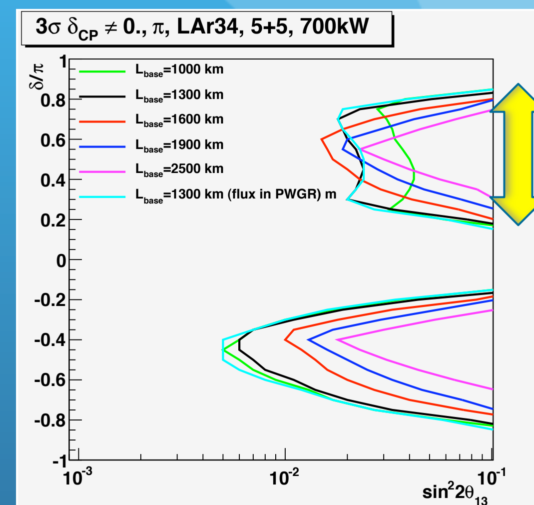
How do sensitivities depend on baseline?

Study done with a Wide Band Beam that is “tuned” to increase with energy as the baseline increases

Curves moving in this direction is good







θ_{13} is relatively independent of L

MH improves with L

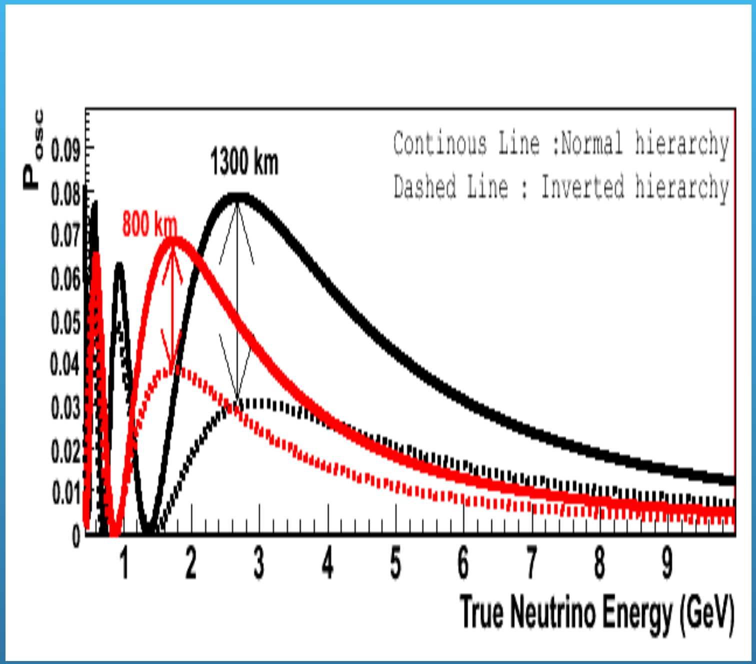
matter and CP asymmetries are coupled

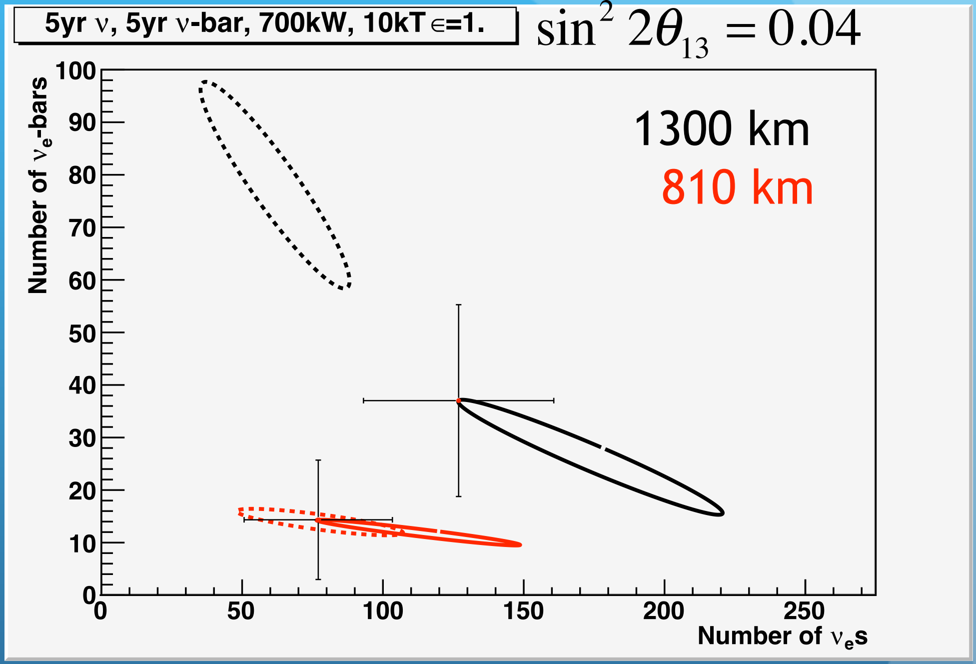
CP asymmetry is a function of θ_{13}

1300 km appears to be nearly optimum if the Mass Hierarchy is unknown and $\sin^2 2\theta_{13} \geq 0.02$

Calculations include 5% systematic errors

What happens at Longer baseline?



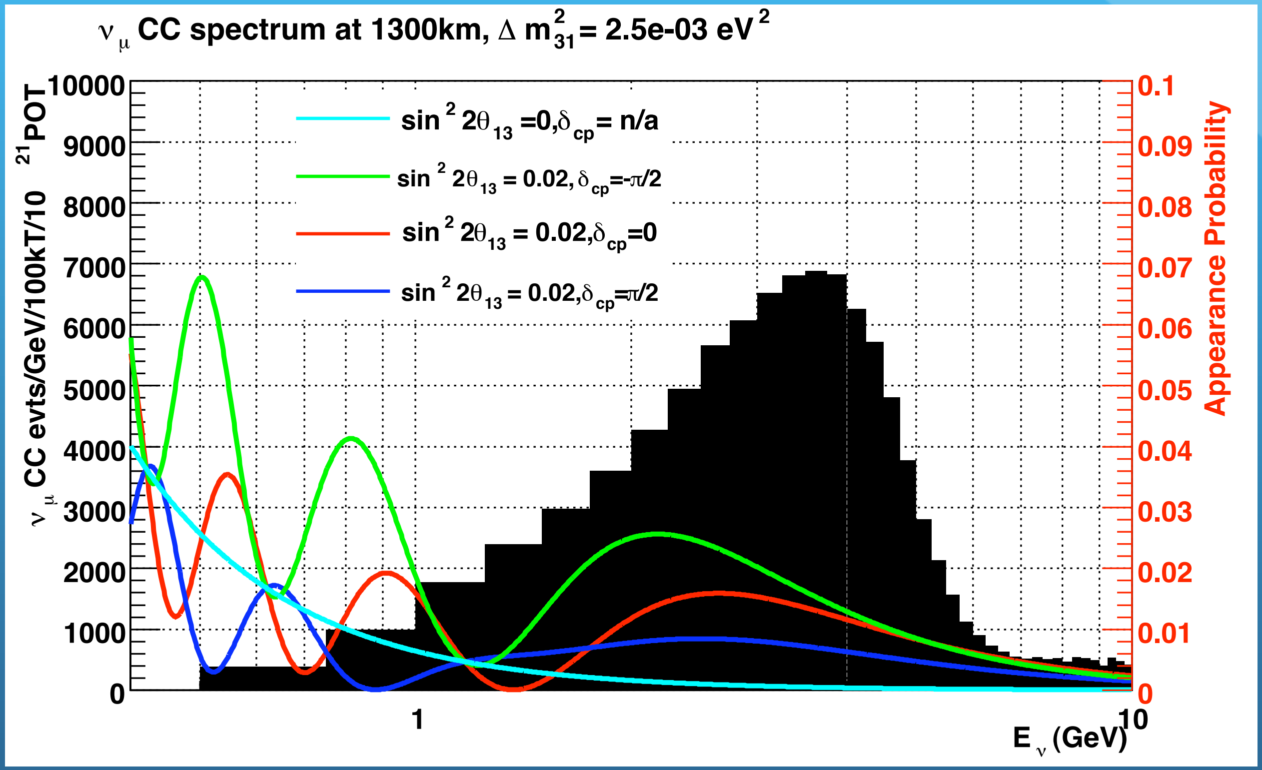


Ellipses form as one varies
$0 \leq \delta < 2\pi$

The matter *effect* which *affects* the oscillation probability increases with *E* and *L*

$$P(\nu_\mu \to \nu_e)_{matter} = f(\theta_{12},\theta_{13},\theta_{23},\delta_{CP},\Delta m^2_{12},(sign)\Delta m^2_{23},E_\nu,L,V_{matter})$$

The oscillation probability has dramatic shape as a function of energy and δ_{CP}



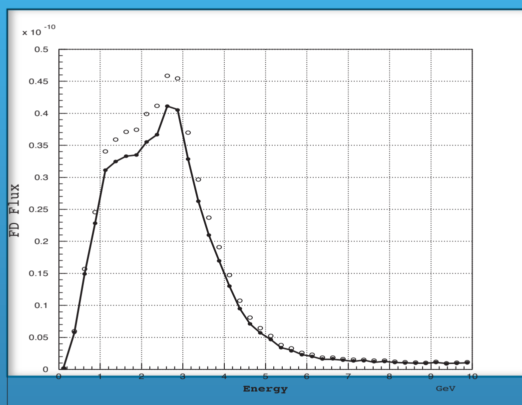
A wide band beam that can span the structure in the oscillation probability provides increased sensitivity over just counting the appearance of events

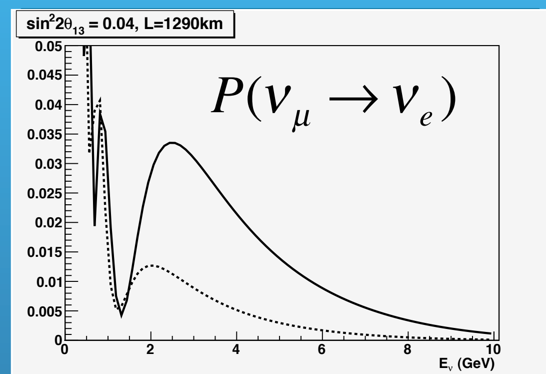
What's the best strategy for a "next-next" generation experiment (i.e. post-NOvA)?

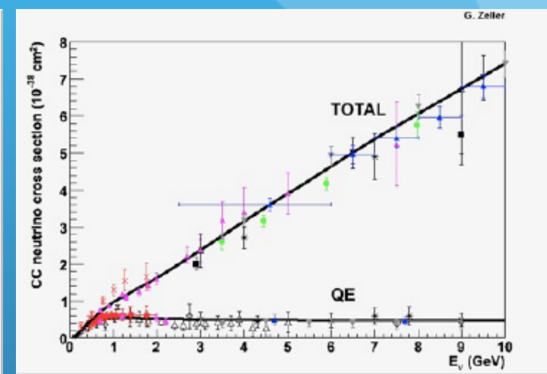
- This is the precise question that the U.S. neutrino community was asked in 2006 for input to the NuSAG Panel
  - A Joint FNAL-BNL study was carried out and several options were explored in detail
    - NuMI Off-Axis (NB) : L< 1000 km; 1st and/or 2nd oscillation maximum; surface locations ➔ LAr technology
    - WBB 2 DUSEL : L = 1300 km; Deep opportunity ➔ WC technology
    - arxiv.org/abs/0705.4396
  - See summary of the NuSAG Report (Summer 2007)
    - http://www.fnal.gov/directorate/Longrange/Steering_Public/files/070716_NuSAG_GB.pdf
    - Bottom line : wait for results on θ_{13} (expected by 2012) and do R&D on detectors and super beams and proton sources

Event rates and detector sizes

$$N_{signal\ produced} = \Phi_{\nu_\mu} \times P(\nu_\mu \rightarrow \nu_e) \times \sigma_{\nu_e}$$







$$N_{detected} = N_{produced} \text{ x detection efficiency}$$

Detection efficiency is a function of the detector technology

Considerations in choosing E, L, Mass and efficiency

- What physics are you trying to do?
- What existing facilities do you have to work with?
- Let's say we're trying to measure $\nu_\mu \to \nu_e$ appearance; ask the question :
  - *What size detector would you need if it had perfect efficiency and background rejection?*
  - Answer is driven by
    - what sensitivity you want to achieve, in the case of no signal
    - your proton beam power ➔ neutrino flux
    - how long you want to run before having a physics result
    - and when are you limited by the intrinsic ν_e's in the beam

For a not too small θ_{13}, reasonable exposure time, long baseline (~1000 km) , conventional neutrino beam created by a protons source (~hundreds of KW), it's in the multi-kTon range

Considerations in choosing E, L, Mass and efficiency

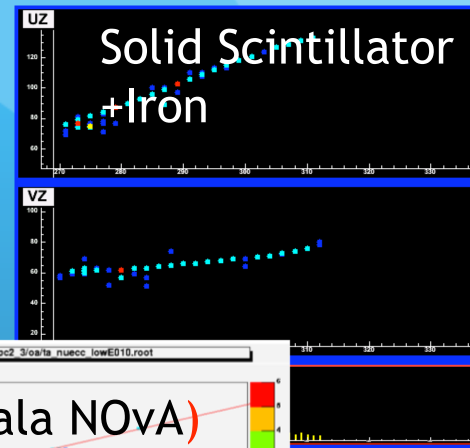
- Finally, ask the question :
  - *For a given detector technology with known (or predicted) efficiency and background rejection, as a function of energy, what detector mass do I need to reach the physics goals that we set out to achieve?*

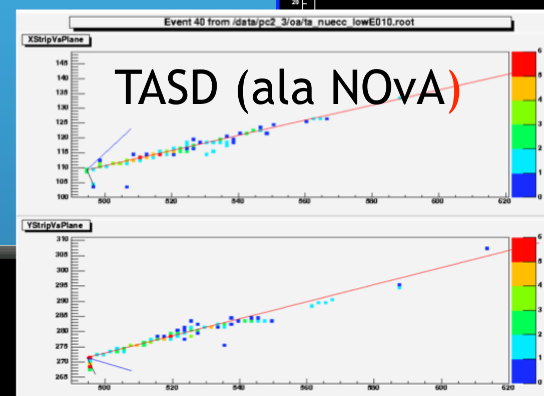
- Performance
  - Signal efficiency & background rejection
    - Depend on event topologies
      - i.e. you need emulsion for high efficiency Tau ID
      - Non-QE events in a Water Cherenkov detector are difficult to reconstruct
      - Neutral currents with pi0s are mis-id's as nue's
    - Topologies depend on neutrino energy
    - Neutrino Energy (where you try to maximize oscillation signals) depends on the baseline
  - Ideally, we would maximize our sensitivity by choosing a detector which performs well (high efficiency, low background) at the energy we have chosen for our baseline

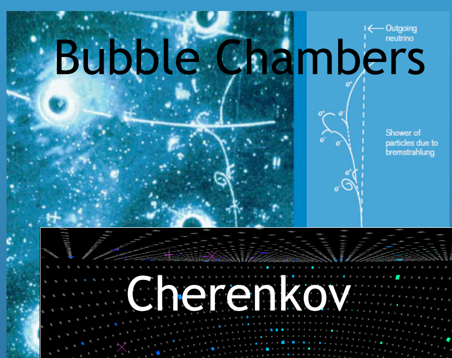
Considerations in choosing E, L, M and efficiency

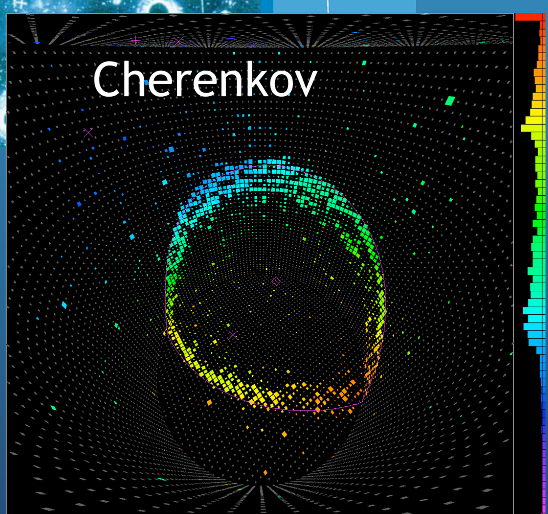
- Major consideration : Cost
  - We all want to get the most bang for our buck
  - Acceptable strategy – sacrifice efficiency for mass if it is more cost effective

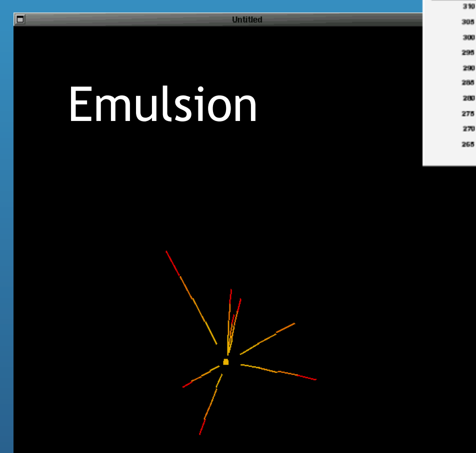
- Additional considerations : Timescale for construction, detector development, risks

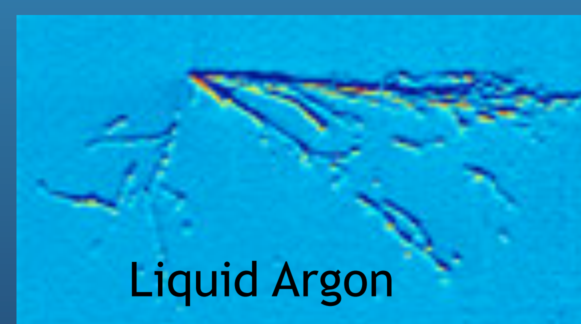




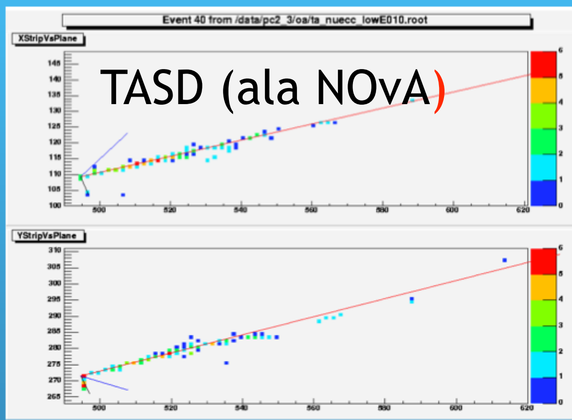


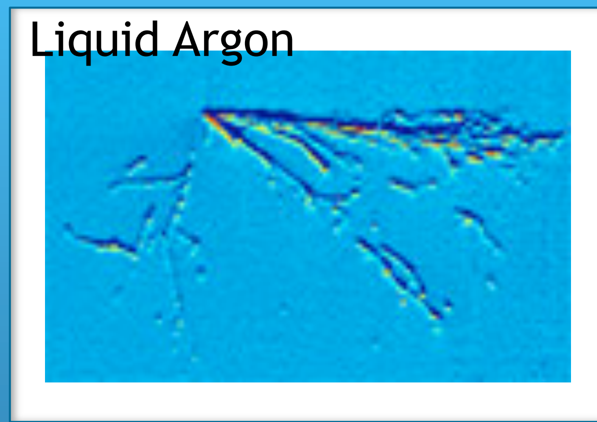


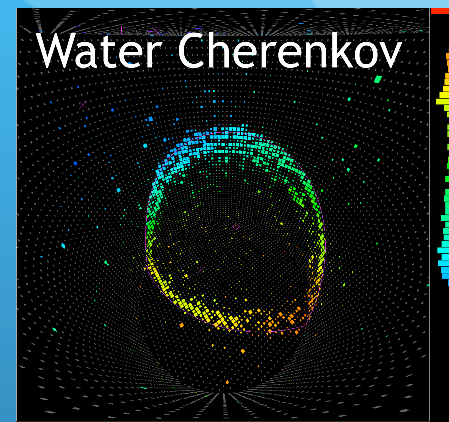




Narrowing the choices : need large mass and excellent resolution for $\nu_\mu \rightarrow \nu_e$

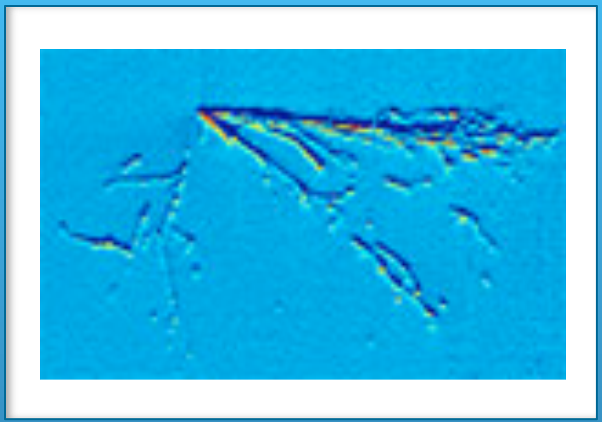


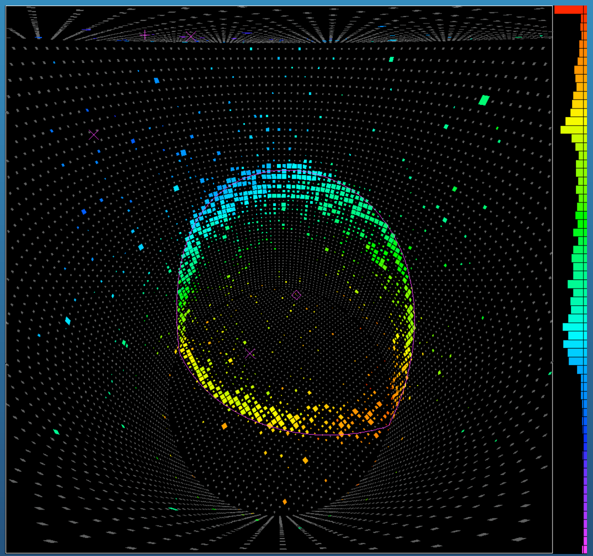




- Considerations :
  - Mass needed to meet the physics goals
  - Cost scaling with mass
  - Maturity of technology
  - Overburden (depth) requirement

Two strategies being pursued for LBNE

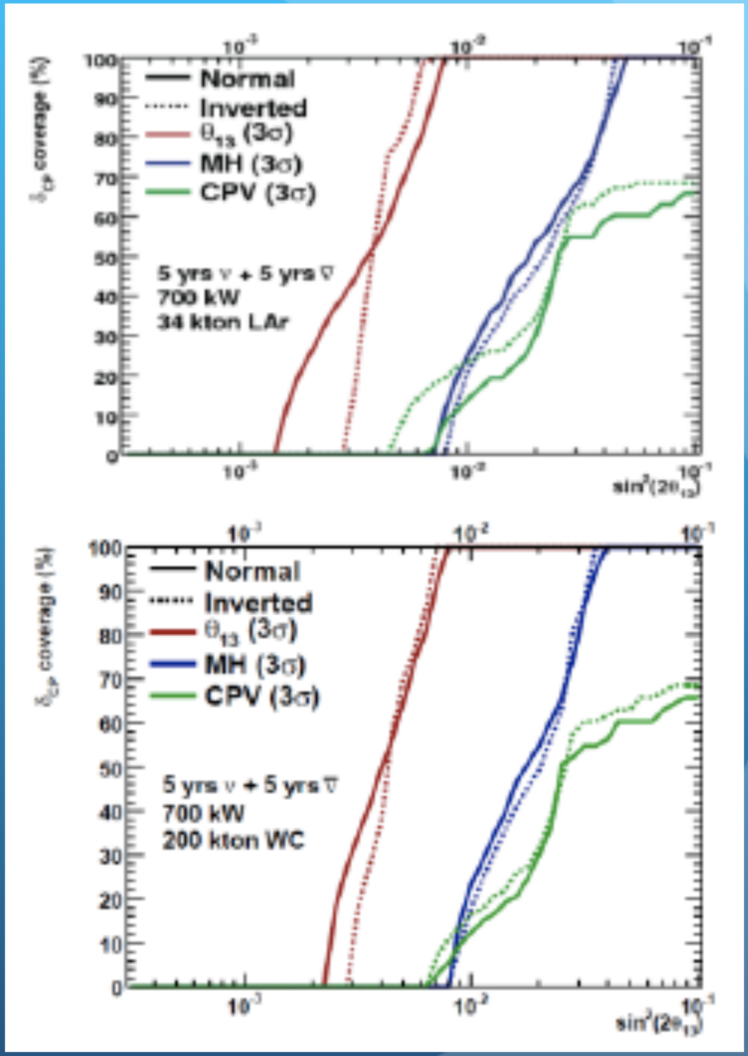




- LAr
  - Aims to reconstruct all of the CC events
  - Efficiency flat with energy above 1 GeV
  - e/gamma separation from position resolution and dE/dx for NCpi0 background rejection
  - Can be smaller compared to other options
    - But it is still a very large detector
  - New technology and scalability to large mass has not been demonstrated
  - Details from B. Fleming tomorrow
- WC
  - Excellent efficiency for CCQE events
  - Efficiency above 1-2 GeV falls due to the CCQE selection criteria
  - In a high energy beam, NCs with pi0s lead to backgrounds that are hard to eliminate
  - Proven technology but needs to be very very large to compensate for reduced efficiency
  - Details from B. Svoboda tomorrow

Physics Sensitivities for LBL $\nu_\mu \rightarrow \nu_e$ oscillations at L = 1300 km

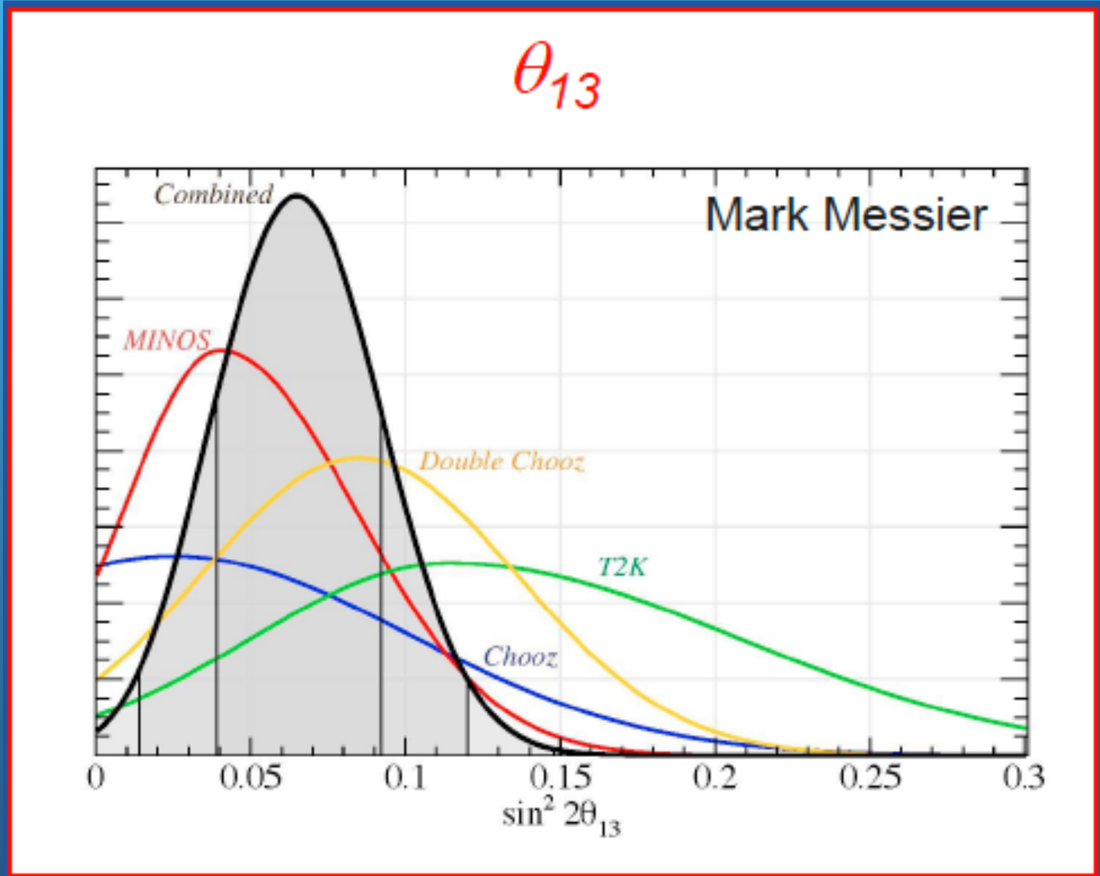
- To achieve the physics reach that one would want in the next generation oscillation experiment (as proposed by LBNE) :
  - Would require ~20-22kT of Perfect Detector (PD)
  - For LAr 34kT is ~ the "PDE"*
  - For WC 200 kT is ~ the "PDE"
- Many factors come into play in determining how to choose



*"Perfect Detector Equivalent"

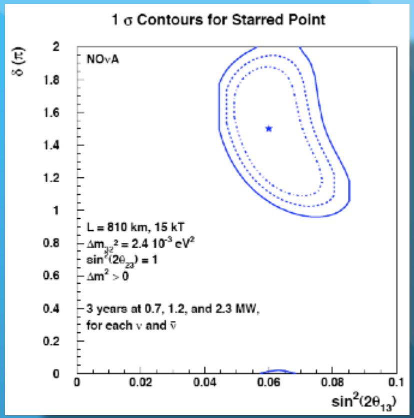
We are approaching 2012 and getting results on θ_{13}

These are indeed exciting times for neutrino physics

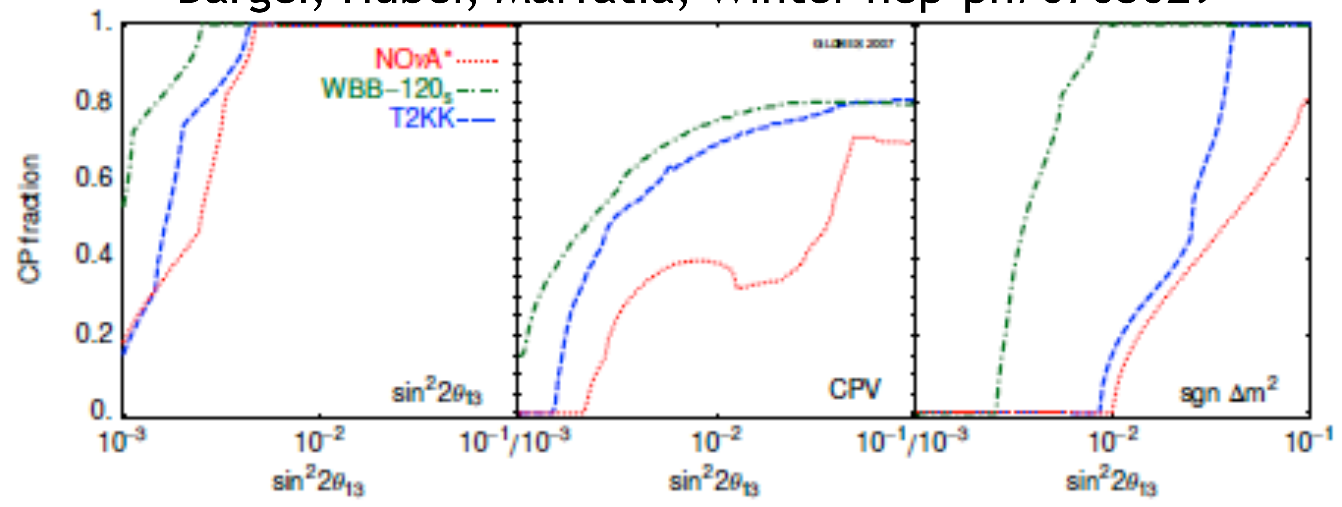


The questions we get asked

- What can we expect to learn from NOvA?
- Would an upgrade to NOvA be a good next step?
- Is the longer-baseline essential?

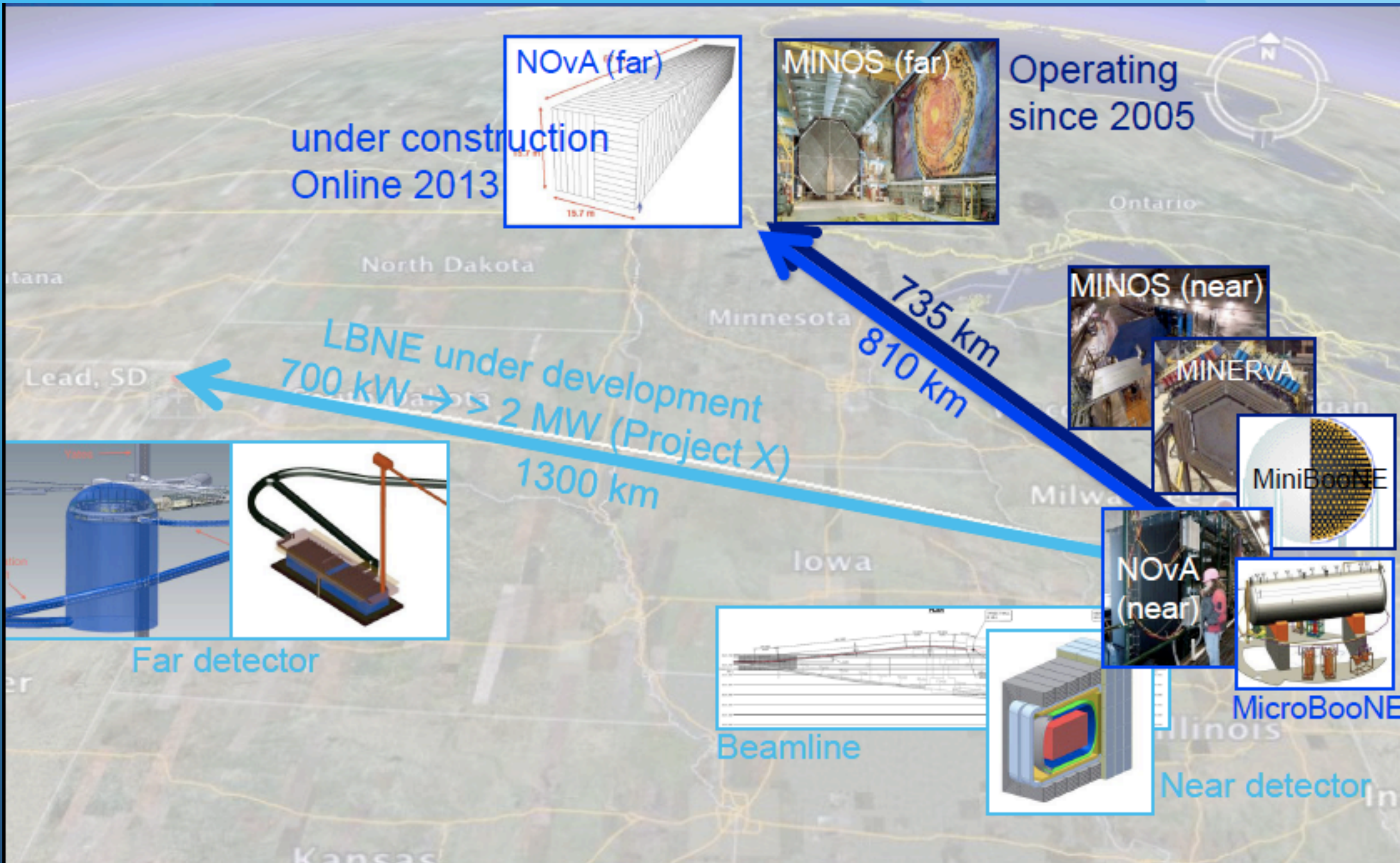


Barger, Huber, Marfatia, Winter hep-ph/0703029



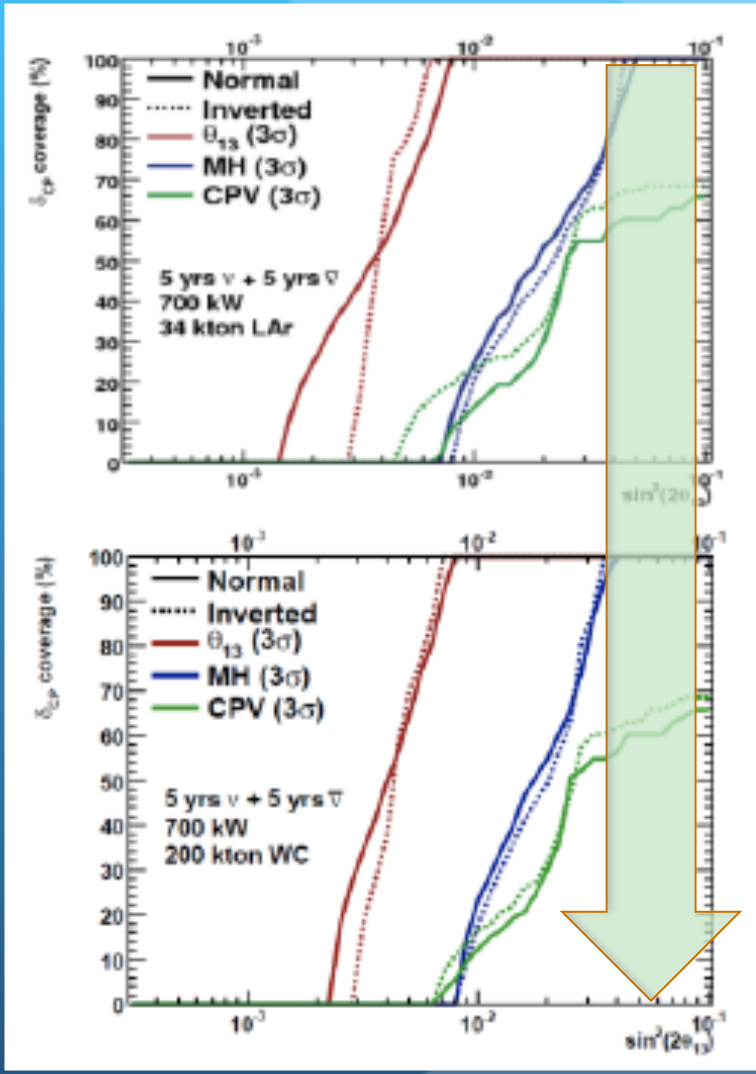
NOvA* & WBB-120 (wide band to 1300km) are 100kT LArTPCs

Neutrinos from Fermilab for the next decades



Implications of large-ish θ_{13} for LBNE

- θ_{13} can be measured to excellent precision (as can NOvA)
- The Mass Hierarchy can almost certainly be unambiguously resolved
- A measurement of δ_{CP} will be a first step in determining if neutrinos violate CP



Summary and Conclusions

- Since the 2007 NuSAG report and the 2008 P5 recommendations we have developed concrete plans for a new long-baseline experiment in the U.S. at a baseline of 1300 km (Fermilab to Homestake)
- In DOE-speak, these plans are approaching the CD-1 level, with a detector technology choice being the last major alternative to be resolved
- All of the next-next generation experiments that are proposed world-wide, including LBNE as currently envisioned, are ambitious and expensive
- We need to be vigilant about watching the science and developing options for our program that can adapt to the fiscal realities

Summary and Conclusions

- Alternative configurations of the long-baseline neutrino experiment, which may be less expensive, and consequently may have less initial reach in physics capability, do exist and can and should be considered
- It's always wise to have a "Plan B"
  - (or even "Plan C")!
- Please keep working and thinking about the BEST way to move our science forward and continue to make progress in unraveling the mysteries of the elusive neutrino

Most quoted words in the titles of the top 100 cited HEP papers!

Thanks to Heidi Schellman !!